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STRENGTH-TOUGHNESS REQUIREMENTS FOR THICK-WALLED HIGH PRESSURE VESSELS

JOSEPH A. KAPP

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US ARMY ARMAMENT RESEARCH,
DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
WATERVLIET, N.Y. 12189-4050

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Joseph A. Kapp

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13. ABSTRACT *(Maximum 200 words)*

The strength and toughness requirements of materials used in high pressure vessels has been the subject of some discussion in the meetings of the Materials Task Group of the Special Working Group - High Pressure Vessels. A fracture mechanics analysis has been performed to theoretically establish the required toughness for a high pressure vessel.

The analysis is based on the validity requirement for plane-strain fracture of fracture toughness test specimens. This means that at fracture, the crack length, uncracked ligament, and vessel length must each be greater than fifty times the crack tip plastic zone size for brittle fracture to occur. For high pressure piping applications, the limiting physical dimension is the uncracked ligament, since it can be assumed that the other dimensions are always greater than fifty times the crack tip plastic zone. To perform the fracture mechanics analysis, several parameters must be known, including vessel dimensions, material strength, degree of autofrettage, and design pressure. Remarkably, the results of the analysis show that the effects of radius ratio, pressure, and degree of autofrettage can be ignored when establishing strength and toughness requirements for design code purposes. The only parameters that enter into the calculation are yield strength, toughness, and vessel thickness. The final results can easily be represented as a graph of yield strength against toughness on which several curves, one for each vessel thickness, are plotted.

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INTRODUCTION

Designing thick-walled high pressure vessels that will fracture only in a ductile manner has been the concern of numerous investigators for many years. The tremendous amount of stored energy contained in an ultrahigh pressure vessel leads us to strive for a design procedure that will ensure some containment capacity of the fractured vessel. This enables the potential energy originally contained inside the vessel to be released in a somewhat controlled manner.

To determine the conditions under which the vessel will fracture, yet maintain some containment capability, can be addressed with a fracture mechanics analysis. With fracture mechanics, it is understood that in a cracked structure, the mode with which the crack grows additionally can be unstable, stable with the structure remaining essentially elastic, or stable with the structure responding in an elastic-plastic or completely plastic manner. Technologies and test methods have been developed for behavior in each of these areas. Applying this fracture mechanics technology to the problem of determining the fracture mode in ultrahigh pressure vessels is not an unreasonable task, if the problem is stated as follows. An unstable fracture event will occur when the vessel responds as if linear elastic fracture mechanics applies. If the conditions of nonlinear elastic or elastic-plastic fracture mechanics apply, then the fracture of the vessel will be stable. A high pressure vessel that fractures in a stable manner is one that is likely to maintain some containment capability even after the fracture event has occurred.

THEORY

The condition for plane-strain fracture of any structure is that at the fracture event, the plastic zone developed at the tip of the crack must be small compared to the other dimensions of the structure. The other critical dimensions are the crack depth, the uncracked ligament, and the out-of-plane dimension. In our case, that of a right circular cylinder, the out-of-plane dimension is the length of the cylinder. The plastic zone size requirement has resulted in the following well-known equation (ref 1):

$$c,d,L \geq 2.5\left\{\frac{K_{Ic}}{\sigma_y}\right\}^2 \tag{1}$$

where c is the crack depth, d is the uncracked ligament, L is the length of the cylinder, K_{Ic} is the fracture toughness, and σ_y is the yield strength.

For the thick-walled high pressure piping case, we can make some assumptions. First, the length of the cylinder will always meet the criterion of Eq. (1). Second, the crack depth will always meet the criterion. This is because the cylinder is a double-connected structure, which means that it requires two complete cuts of the wall thickness to cut the cylinder into two pieces. Multiple connection in any structure increases the stiffness of the structure significantly, constraining it more than if it were a single-connected structure. Constraint is the determining factor for brittle or ductile behavior. If the crack tip is sufficiently constrained such that the crack can only relieve itself by elastic energy release rather than by dissipation in plastic flow, then the fracture will be brittle. When the criterion of Eq. (1) is applied to the crack depth, the crack must be constrained enough so that a large deformation at the crack tip will not allow the crack to deform so much that it turns into a notch rather than a crack. The additional constraint of the multiple connection does not permit even a small crack to deform greatly. Therefore, it can be assumed that the crack depth criterion of Eq. (1) will always be met.

The only dimension left is the uncracked ligament. The requirement for the uncracked ligament is that it must be large enough so that the fracture event remains elastic. Therefore, the uncracked ligament governs the fracture mode behavior of high pressure pipe. Equation (1) can now be rewritten as:

$$d=(t-c)\geq 2.5\left\{\frac{K_{Ic}}{\sigma_y}\right\}^2 \tag{2}$$

In this equation, t is thickness of the vessel or pipe. To find the minimum fracture toughness for a given vessel and yield strength, we replace the inequality with an equality. We then add the condition that the applied stress intensity factor, K, is equal to the fracture toughness. The applied stress intensity factor is a superposition of the stress intensity factor from the applied pressure, K_p, and the stress intensity factor due to autofrettage, K_a. Stated mathematically, the condition at fracture is

$$K_{Ic}=K=K_p+K_a=\sigma_p\sqrt{\pi c}\,f_p\left\{\frac{c}{t}\right\}+\sigma_a\sqrt{\pi c}\,f_a\left\{\frac{c}{t}\right\} \tag{3}$$

where σ_p is the tangential stress at the bore due to the applied pressure p, and σ_a is the residual tangential stress at the bore from autofrettage. The functions f_p and f_a are the crack depth correction factors for the pressure loading condition or autofrettage loading condition, respectively. By solving Eqs. (2) and (3) simultaneously, relationships between yield strength and fracture toughness may be obtained. However, the relationship between strength and toughness is a function of several other parameters. Solving Eqs. (2) and (3) simply eliminates the crack depth. The pressure, thickness, radius ratio, and degree of autofrettage must also be assumed. Thus, at first glance, it appears that the strength-toughness relationship required to ensure against plane-strain fracture is not a simple relationship.

NUMERICAL RESULTS

The required result from the simultaneous solution of Eqs. (2) and (3) is a value of fracture toughness for a given yield strength. This can only be obtained if the thickness, degree of autofrettage, pressure, and radius ratio are held constant. The specific equations necessary are as follows:

For pressure loading:

$$\sigma_p=p\left\{\frac{2k^2}{k^2-1}\right\} \tag{4}$$

$$f_p\left\{\frac{c}{t}\right\}=1.11-0.446\left\{\frac{c}{t}\right\}+1.089\left\{\frac{c}{t}\right\}^2 \tag{5}$$

For autofrettage loading (100 percent overstrain):

$$\sigma_a=\sigma_y\left\{1-\ln(k)\frac{2k^2}{k^2-1}\right\} \tag{6}$$

$$f_a\left\{\frac{c}{t}\right\}=1.11-1.806\left\{\frac{c}{t}\right\}+0.839\left\{\frac{c}{t}\right\}^2 \tag{7}$$

where k is the radius ratio and the other parameters are defined above. The equations for the stresses, Eqs. (4) and (6), are the Lamé stress evaluated at the bore and the tangential residual stress at the bore calculated assuming the Tresca yield criterion, respectively. The polynomials for crack depth correction factors f_p and f_a are numerical fits to the stress intensity factor solutions by Parker et al. (ref 2). These functions can only be assumed to be approximate, since the stress intensity factor solutions are presented graphically in Reference 2.

As stated above, the required toughness for a given strength is a function of numerous variables. The effects of each of these parameters are presented and discussed in this report.

The first variable is the effect of design pressure. Figure 1 demonstrates the combined effects of design pressure and strength on the required toughness of a given section thickness and radius ratio. The curves for each strength level were terminated at the elastic strength pressure of the vessel. Some general comments can be made. Examining the effects of strength at a constant pressure reveals that the higher the strength, the smaller the crack tip plastic zone for a constant applied stress intensity factor. Therefore, all other factors being equal, the required toughness must be greater. Similarly, with all other parameters held constant, the effects of design pressure are easily explained. If we have a vessel of known dimensions and material strength, loading that vessel with a low pressure will result in a low applied stress intensity factor. The critical crack size will be large and the uncracked ligament will be small. When the uncracked ligament is small, the fracture toughness required is small. Loading the same vessel at higher pressures will produce higher stress intensity factors, corresponding shorter critical crack depths, and larger uncracked ligaments. A large uncracked ligament requires higher toughness.

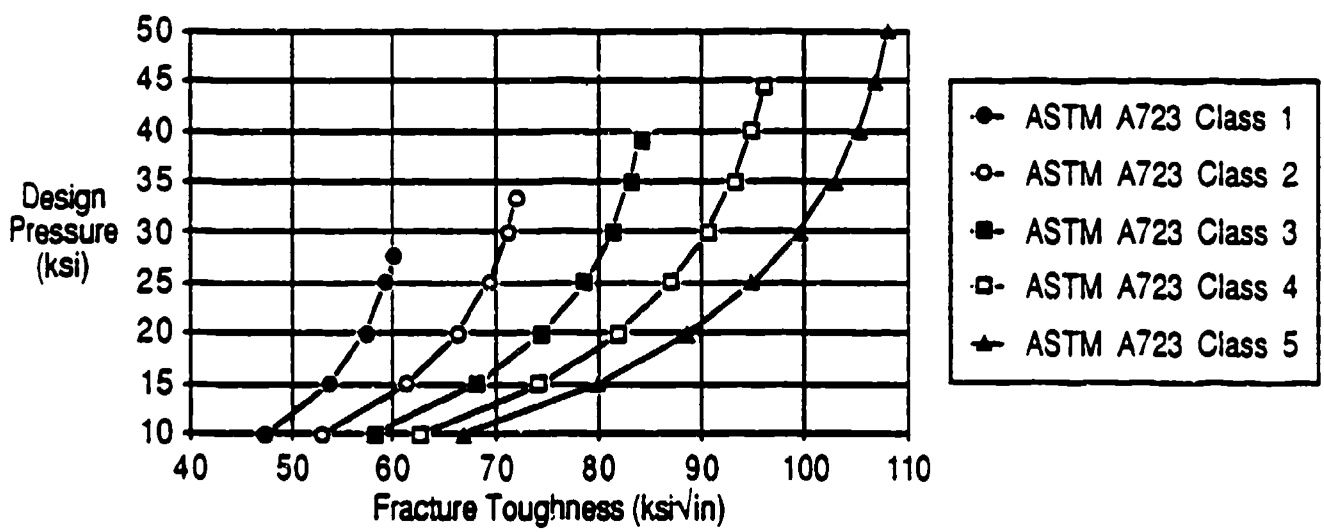

Figure 1. The effects of strength on toughness requirements for a vessel with a 1.0-inch wall thickness, radius ratio of 1.5, and no autofrettage.

Curves such as Figure 1 can prove worthwhile during the design of a vessel. If the design of the vessel is fixed, including design pressure and yield strength, a unique toughness is required. However, for the purposes of design code development, it can be assumed that for a given yield strength and section thickness, the vessel will always be operated at its maximum elastic capacity. If that vessel is operated at pressures less than its elastic strength pressure, the required toughness is actually less than that required at a higher pressure.

The second variable is the effect of radius ratio on the required toughness. This is attempted in Figure 2, where the required toughness as a function of design pressure for different radius ratios is plotted given a constant thickness, yield strength, and no autofrettage. The effects of varying radius ratio with all other parameters being fixed (including pressure) show that as the radius ratio is increased, the toughness requirement is relaxed. This is due to the strength of the vessel. At a constant design or operating pressure with a constant wall thickness, increasing the radius ratio decreases the applied stress. When the stress is decreased, the applied stress intensity factor is also decreased. Therefore, the critical crack size is increased, and the uncracked ligament is decreased. The smaller the uncracked ligament, the less the required fracture toughness. An interesting observation to make here is that regardless of the radius ratio for a given wall thickness and strength, the required fracture toughness is a constant for operating the vessel at its elastic strength pressure.

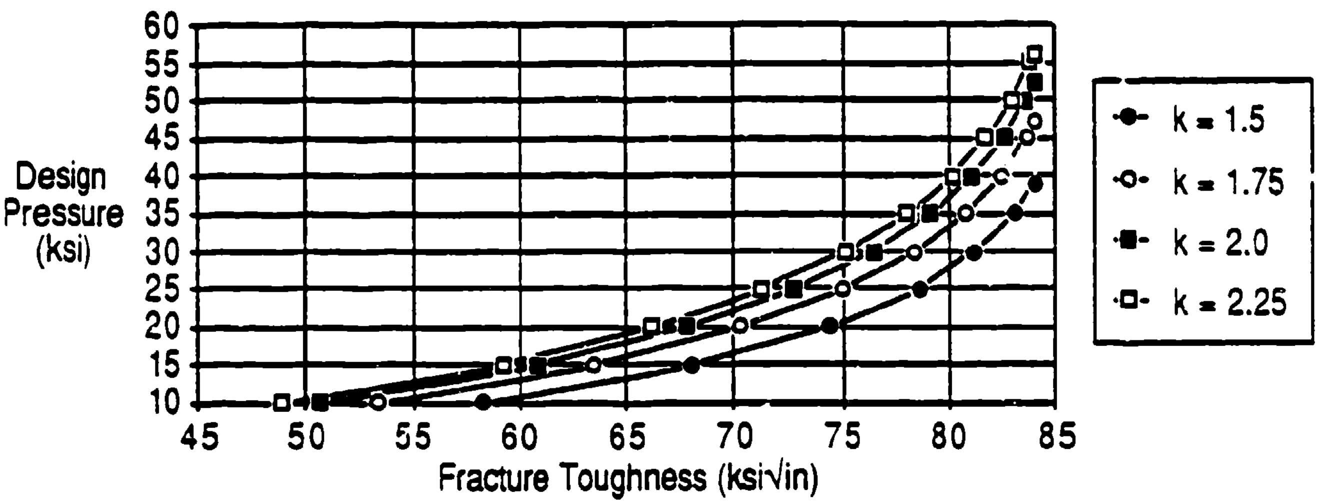

Figure 2. The effects of radius ratio on toughness requirements for a vessel with no autofrettage, a wall thickness of 1.0 inch, and made from ASTM A723 Class 3 steel.

This observation deserves some discussion. The reason for the invariance of toughness with radius ratio can be explained mathematically by examining Eqs. (2) and (3). Here we have that the requirement for ductile fracture is determined by the ratio of the fracture toughness to the yield strength, when the applied stress intensity factor is equal to the fracture toughness. Therefore, the fracture toughness term in the numerator of Eq. (2) is replaced by the applied stress intensity factor term in Eq. (3), which is the applied stress times some correction factor. The only variable that is affected by the radius ratio is the applied stress. All other terms are independent of the radius ratio. At the vessel's elastic strength pressure, the applied stress is equal to the yield strength regardless of the radius ratio. Therefore, when a vessel is operated at its elastic strength pressure, the fracture toughness required to ensure ductile fracture is not a function of the radius ratio. It should be pointed out here that the crack depth correction factors f_p and f_a were fit to stress intensity factor solutions for vessels with a radius ratio of two. There is some effect of radius ratio on these correction factors. In other words, f_p should be a function of crack depth and radius ratio and not just crack depth. This introduces some error in the results reported here. To quantify the magnitude of the error, the following example was calculated. The crack depth correction factor was determined using the stress intensity factor solutions reported by Bowie and Freese (ref 3) for a radius ratio of 1.6. The analysis outlined above was conducted, and a three percent error was introduced. Larger errors may be introduced if this analysis is applied to thin-walled vessels. The reader is cautioned that the results obtained herein are only valid for thick-walled cylinders.

The third variable to be evaluated is the effect of autofrettage residual stresses. One would think that the effect of autofrettage itself would be great. The numerical results are shown in Figure 3. In this figure, two identical vessels are compared. The only difference is that one vessel has been autofrettaged 100 percent overstrain, and the other has no residual stresses. The results show that autofrettage indeed gives you a great advantage. For the same operating pressure, less fracture toughness is necessary to ensure ductile fracture if the vessel is autofrettaged. The remarkable observation from Figure 3 is that if the autofrettaged vessel and the nonautofrettaged vessel are both operated at their respective elastic strength pressures, then the toughness requirements are essentially the same.

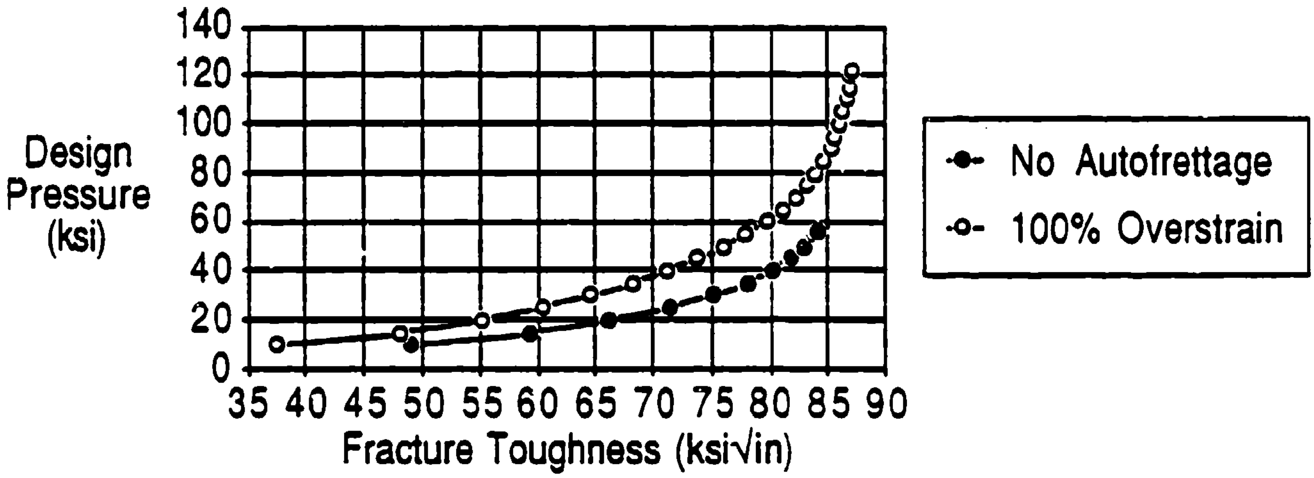

Figure 3. The effects of autofrettage on toughness requirements for a vessel manufactured from ASTM A723 Class 3 steel, with a radius ratio of 2.25 and a wall thickness of 1.0 inch.

The reason for this is similar to the reason for the radius ratio effect, but it is a little more difficult to see. It is worthwhile in this case to write it out. The following is the ductile fracture criterion:

$$(t-c)=2.5\left\{\frac{K_{Ic}=\sigma_p\sqrt{\pi c}\ f_p\left\{\frac{c}{t}\right\}+\sigma_a\sqrt{\pi c}\ f_a\left\{\frac{c}{t}\right\}}{\sigma_y}\right\}^2 \tag{8}$$

The solution of Eq. (8) occurs when the value of c is as small as possible. This results in the largest uncracked ligament and therefore the largest required fracture toughness. When the crack is small, the values of both f_p and f_a approach the limiting solution of 1.12. When the cracks are small, then it can be said that f_p and f_a are equal and can be factored out leaving the following:

$$(t-c)=2.5\left\{\frac{1.12(\sigma_p+\sigma_a)\sqrt{\pi c}}{\sigma_y}\right\}^2 \qquad (9)$$

At its elastic strength pressure, the value of the sum $\sigma_p + \sigma_a$ is equal to σ_y, and this cancels with the denominator of Eq. (9) resulting in the same condition for determining the minimum required toughness whether or not the vessel is autofrettaged. There is some difference, because the two crack depth correction factors are not exactly equal, and a slightly greater toughness is required when the autofrettage component is included. Another reason for an autofrettaged vessel requiring greater toughness is the manner in which the autofrettage is introduced into the analysis. Kendall (ref 4) has claimed that to accurately predict the fatigue crack growth in autofrettage thick-walled cylinders, it must be assumed that the stress intensity factor produced from the autofrettage residual stresses is less than that calculated from numerical stress intensity factor solutions. In the same report, Kendall does state that the full residual stress should be included when considering fracture. Some recent work by Banks-Sills and Marmur (ref 5) suggests that the same reduction factor on the residual stress component of the stress intensity factor should apply to the fracture of cylinders as well. In this paper, it was found that measuring fracture toughness in disks cut from identical autofrettaged and nonautofrettaged cylinders and tested with the residual stress still present was different. The authors state that the residual stress decreases the fracture toughness, but the experimental observation could also be explained by stating that not all of the residual stresses effect is seen by the cylinder. Therefore, in the work reported here, it was assumed that not all of the residual stresses assist in the prevention of fracture. The value of σ_a used to determine toughness requirements is the value of σ_a calculated from Eq. (6) multiplied by the factor 0.7, as suggested by Kendall.

The conclusion to be drawn from the above numerical experiments is that the following design variables really do not enter into the strength-toughness material requirements for high pressure vessel applications: design pressure, radius ratio, and autofrettage. The only governing factor is the wall thickness. The required strength and toughness for several thicknesses are shown in Figure 4. The four plots presented demonstrate two trends. First, as the thickness increases, the fracture toughness necessary to ensure ductile fracture increases. This was an expected result, since brittle fracture is much more likely with large section sizes than with small section sizes. Second, for a given thickness, as the strength increases, the toughness requirements increase. This is the case, because as the strength increases, the size of the plastic zone decreases, thus a larger toughness will be required with high strength than with low strength.

An interesting comparison to make at this point is the difference, if any, brought about by using the above analysis or the limiting case. The minimum toughness requirement for a given strength and thickness occurs when the critical crack size is minimal. This maximizes the uncracked ligament. The trivial case would be that the critical crack length is zero, and the uncracked ligament is the wall thickness. This leads to the equation

$$t=2.5\left\{\frac{K_{Ic}}{\sigma_y}\right\}^2 \qquad (10)$$

Comparing this limit to the strength and toughnesses calculated and plotted in Figure 4, the plot in Figure 5 is generated. Only two thicknesses are shown here: 1.0 and 8.0 inches. As is clearly observed, there is little difference between the required strength and toughness developed using a rigorous fracture mechanics approach and those obtained from Eq. (10). The maximum difference is about five percent.

Therefore, for design code purposes, the rigorous analysis that has been developed here may not be absolutely necessary. The required strength and toughness for a given wall thickness can be calculated from Eq. (10).

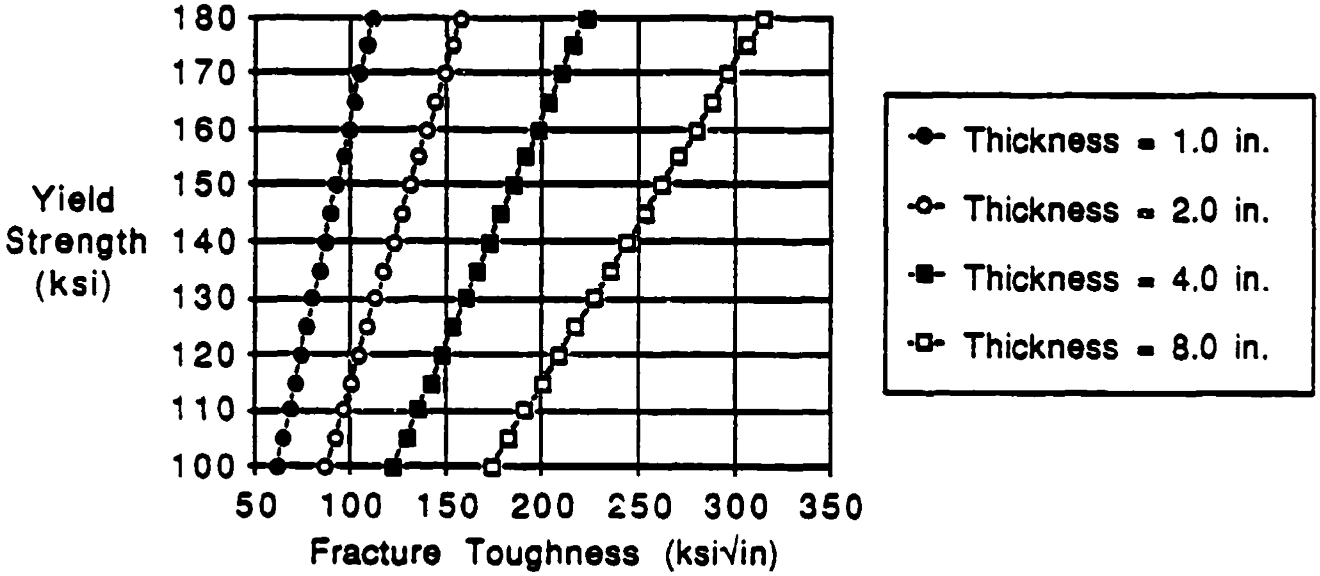

Figure 4. The effects of wall thickness on the strength-toughness requirements calculated assuming 100 percent overstrain autofrettage residual stresses.

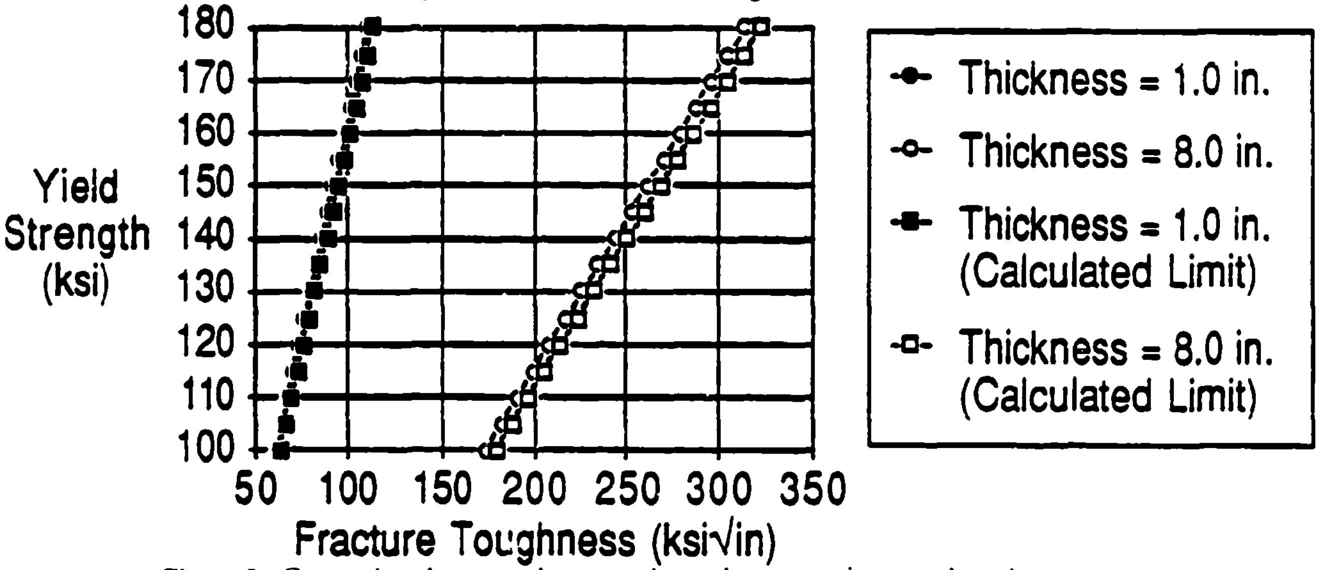

Figure 5. Comparison between the strength-toughness requirements based on rigorous fracture mechanics analysis and the trivial limiting case.

Figure 5 plots the strength and toughness requirements with toughness measured as fracture toughness. This is a requirement from the fracture mechanics analysis used. However, it is sometimes more convenient to express toughness in terms of Charpy impact strength. If it is assumed that the Barsom and Rolfe (ref 6) correlation between fracture toughness and Charpy impact strength applies to ASTM A723 steel, then Figure 4 can be replotted. This is presented here as Figure 6. Since the plots shown in Figure 6 are based on the calculation using Eq. (10), the required impact strength for a given yield strength and wall thickness can be written as follows:

$$CVN = \sigma_y(0.08t + 0.05) \tag{11}$$

where CVN is the Charpy V-Notch impact strength in units of ft-lbs, σ_y is the yield strength in Ksi, and t is the wall thickness in inches.

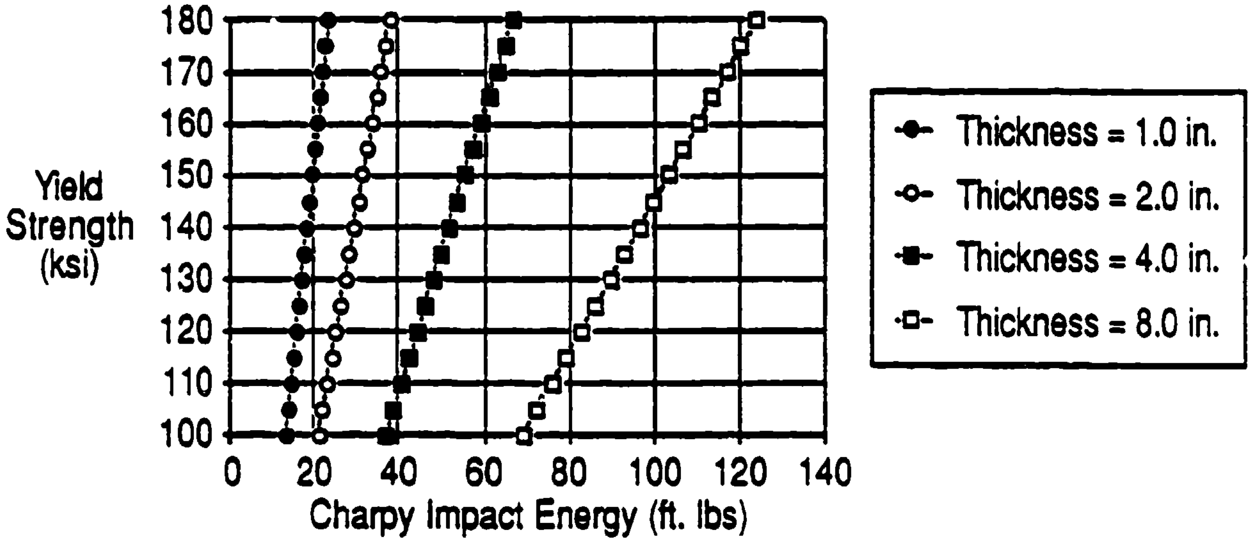

Figure 6. Strength-toughness requirements (toughness in terms of CVN impact strength) as a function of wall thickness. The assumption is that the Barsom and Rolfe correlation applies.

It is not at all certain if the toughness values in the plot are conservative or overly conservative. The effect of design pressure and crack shape may relax the toughness requirement somewhat. For example, the elastic strength pressure is calculated as 56 Ksi for a vessel 10 inches thick, a radius ratio of 1.5, fabricated from material with 130 Ksi yield strength, and autofrettaged 100 percent overstrain. At its elastic strength pressure, the required fracture toughness is a little more than 250 Ksi$\sqrt{\text{in}}$. If the vessel is operated at only 30 Ksi, the toughness requirements are reduced to a little less than 230 Ksi$\sqrt{\text{in}}$., a reduction of about 10 percent. Changing the crack shape has the same effect as reducing the pressure, in that the applied stress intensity factor is reduced. The stress intensity factor at the tip of a semicircular crack at deepest penetration is only about two-thirds of what the stress intensity factor would be if the crack were straight. If we assume that the crack shape effect scales with the pressure effect, then an additional relaxation of the toughness requirement of about 10 percent may be all that can be expected. The combined 20 percent relaxation of the toughness requirement gives the designer some relief.

The real factor that determines if the toughness values plotted in Figures 4 and 5 are overly conservative or not is the effect of pressure in the crack. The pressure in the crack will increase the applied stress intensity factor, but it will also change the crack tip constraint conditions. Remember that the entire exercise reported here is based on the assumption that the crack tip plastic zone is some fraction of the remaining ligament. The size of the plastic zone is calculated by assuming that the material at the crack tip is subjected to uniaxial tension. That is clearly not the case with a pressurized crack. The loading is biaxial, and the second component is a compressive pressure stress. The presence of the pressure in the crack should increase the crack tip plastic zone size, thereby decreasing the required toughness. The pressure in the crack could have a drastic effect on the fracture mode. Until there is some way of quantifying this effect, either experimentally or analytically, the plots in Figures 4 and 5 should serve as guidance to determine the strength and toughness requirements for design code purposes.

SUMMARY AND CONCLUSIONS

By performing a fracture mechanics analysis, the strength and toughness requirements have been calculated to ensure stable fracture of a high pressure vessel. The final results presented in Figures 4 and 5 were determined using a conservative analysis. The conservative assumptions made are (1) the vessel is operating at its elastic strength pressure; (2) the cracks that exist in the vessel are straight-fronted cracks; and (3) the effect the pressure in the crack has on the fracture behavior of the vessel is ignored. It is clear that with very thick vessels, the toughness required by the analysis may exclude such vessels from meeting design code requirements because materials do not exist that have the required properties. Some relief may be granted the designer if the vessel is to be operated at pressure levels well below its elastic strength pressure, and the analysis outlined here is performed to determine the actual toughness required.

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